1.8 Fifth Symposium on Integrated Observing System, 14-19 January 2001, Albuquerque, NM

DELAYED-MODE CALIBRATION OF PROFILING FLOAT SALINITY DATA BY HISTORICAL HYDROGRAPHIC DATA +

Annie P.S. Wong *, Gregory C. Johnson ♣ and W. Brechner Owens ♥
JISAO, University of Washington, Seattle, Washington *
NOAA/PMEL/OCRD, Seattle, Washington ♣
Woods Hole Oceanographic Institution, Woods Hole, Massachusetts ♥

1. INTRODUCTION * +

CTD profiling floats are instruments that drift with the ocean current at a fixed parking depth and rise to the sea surface at regular time intervals. While rising to the surface, the float takes a profile of temperature and conductivity versus pressure through the water column. From these variables, salinity, depth and density can be calculated. The data are sent to various data centers via satellites, before the float sinks back to its prescribed parking depth to continue its drift. The ARGO program (http://www-argo.ucsd.edu) plans to deploy 3000 such CTD profiling floats to observe temperature, salinity and currents within the upper layers of the global ocean.

These profiling floats presently have a lifespan of about 4 years, and are expected to give good measurements of temperature and pressure over their lifetime. However, salinity measurements may experience sensor drifts owing to bio-fouling and a variety of other problems. Unlike traditional CTD casts, where in-situ bottle data are usually obtained for salinity calibration, “ground-truth” salinity data do not accompany these floats. The moving nature of these floats also means that only a few can be retrieved for laboratory salinity calibrations. We discuss a system being built to calibrate the salinity data from these profiling floats with nearby historical hydrographic data.

2. SALINITY CALIBRATION BY θ-S CLIMATOLOGY

The two main state variables of the ocean, potential temperature, θ, and salinity, S, are related to each other by definite patterns that are characteristic of a region (e.g. Emery and Dewar, 1982). Even though these θ-S relationships are influenced by eddies and seasonal/decadal variations, they provide a basis for estimating what the ocean should look like at any given point, within the bounds of variability. Climatological θ-S relationships are generally more stable deeper in the water column and further from ventilation regions. These climatological θ-S relationships are here used to calibrate the salinity data from the profiling floats.

2.1 *A world θ-S climatology database*

To establish a θ-S climatology for the world ocean, measurements from a selected subset of both CTD and bottle data from the World Ocean Database 1998 (WOD98) have been assembled and interpolated onto standard θ levels. The float salinity measurements are later compared to the estimated climatological salinity field on these standard θ surfaces. Standard θ surfaces are used rather than standard density surfaces, because errors in salinity lead to errors in density. In other words, the two state variables θ and S are kept separate. The float salinity data are essentially calibrated using the more accurate float temperature measurements as the dependent variable.

To capture most of the water column for the world ocean, 54 standard θ levels have been selected between –1°C and 30°C. Interpolation has been done from the deepest level to the shallowest. In cases of θ inversions, salinity on the deepest instance of each isotherm is retained. This choice is made to utilize the larger and more stable part of the water column below the shallow temperature inversions. All interpolated historical salinity data have been visually inspected for wild outliers, which have subsequently been removed.

**Corresponding author address*: Annie Wong, NOAA/PMEL/OCRD, 7600 Sand Point Way, Bldg. 3, Seattle, WA 98115-6349, USA; awong@pmel.noaa.gov.

+ JISAO Contribution # 789; PMEL Contribution # 2258.

2.2 ***Objective estimates of θ-S curves at float locations***

These interpolated historical salinity data on standard θ surfaces are then used to estimate the climatological θ-S relationships at the float profile locations. For each float profile, a group of "best" 500 historical points in a 20° x 20° square around the profile is selected for every standard θ surface. If fewer than 500 historical points are available, then all available points are used. The "best" 500 points consist of 250 points that have the strongest spatial correlations with the float profile location, and another 250 points with the strongest spatial-temporal correlations.

The correlation calculations depend on 3 scale variables: a longitudinal scale, a latitudinal scale, and a temporal scale. The two spatial scales have been somewhat arbitrarily set at Lx = 8° (longitudinal) and Ly = 4° (latitudinal), based on regional water mass variability scales. Work is in progress towards a less ad-hoc method for determining the spatial scales. Also, a refinement will be to rotate the axes so the longer mapping scales become parallel to coastlines when the floats are near the coasts. For the temporal scale, a global data set of CFC (chlorofluorocarbon) apparent ages (e.g. Doney and Bullister, 1992) has been obtained (pers. comm. J. Bullister) to provide an approximate ventilation time scale τ for water at various θ levels. The maximum CFC apparent age is about 50 years, so some error in the time weighting is expected in "older" water masses.

An objective mapping technique is then used to estimate the climatological θ-S relationship at each float profile location, using the selected historical points. The advantage of using the objective method is that it gives a pointwise estimate that is linear and unbiased, and also returns an estimate of its own error variance that takes into account the distribution of the data used (e.g. Roemmich, 1983; McIntosh, 1990).

The objective estimate at each location and on each standard θ surface is given by $\mathbf{d} + \underline{\omega} \cdot (\underline{d} - \mathbf{d})$, where $\underline{d}$ denotes the group of selected historical data for that standard θ surface, and **d** denotes the mean value of the group. In other words, the *a priori* estimate is assumed to be **d**, the mean value of $\underline{d}$. Signal and noise variances of the group of selected historical points are estimated and are taken into account in the coefficient matrix $\underline{\omega}$. The noise variance represents the random processes in the ocean that cause deviations from the climatology, such as influences of eddies and seasonal/decadal variations, as mentioned previously.

The coefficient matrix $\underline{\omega}$ takes the form $\underline{\omega} = C\mathrm{dg} \cdot C\mathrm{dd}^{-1}$, where *C*dg denotes the data-grid covariance matrix, and *C*dd denotes the data-data covariance matrix. The covariance function is Gaussian. A two-stage mapping is employed. In the first stage, the covariance function involves only the spatial scales Lx and Ly, and takes the form:

$$\exp\left(- \left[(x_i - x_j)^2/Lx^2 + (y_i - y_j)^2/Ly^2 \right] \right) .$$

This stage represents the climatological spatial mean without respect to the temporal variability. In the second stage, the residuals from the first stage are mapped with a covariance function that involves both the spatial and the temporal scales:

$$\exp\left(- \left[(x_i - x_j)^2/Lx^2 + (y_i - y_j)^2/Ly^2 + (t_i - t_j)^2/\tau^2 \right] \right) .$$

The second stage map thus gives increased weight to the more recent data.

The final estimate is the result of the two stages of mapping. Therefore the best objective estimate comes from historical data that are not only close to the float profile location in space (relative to the spatial scales), but are also close to the float profile location in time (relative to the ventilation time scale). If the time differences between the historical data and the float measurements differ by more than the ventilation time scale, the spatial-temporal covariance will be small, and so the second stage contribution will be negligible. The final estimate will relax back to the first stage map, or the mean spatial climatology. If the float drifts into areas with no CFC apparent age estimates, such as marginal seas, the second stage map will map the residuals with a spatial covariance function only.

The objective estimate is a least square estimate, with the error variance of the estimate given by:

$$\text{signal variance} - C\mathrm{dg} \cdot C\mathrm{dd}^{-1} \cdot C\mathrm{dg}' .$$

The error from the second stage map is taken to be the error of the objective estimate, since it realistically gives increased error estimates where recent data are not available and/or apparent ages are low.

2.3 *Weighted least squares fit for a time-varying slope in conductivity space*

The float salinity data are then fitted to the objectively estimated climatological salinity field. To do this, a multiplicative time-varying slope term is calculated in potential conductivity space by weighted least squares, with the weights proportional to the inverse of the salinity mapping errors. Weighing the calibration model by the salinity mapping errors means that the deeper surfaces where the θ-S relationships are tight are used more heavily in the calibration. Calculations are done in potential conductivity space because conductivity is the measured parameter here, and using potential conductivity eliminates the differences in the pressures of the standard θ surfaces between historical and float data. A multiplicative correction is appropriate for correcting changes in conductivity cell geometry through accretion or ablation of material.

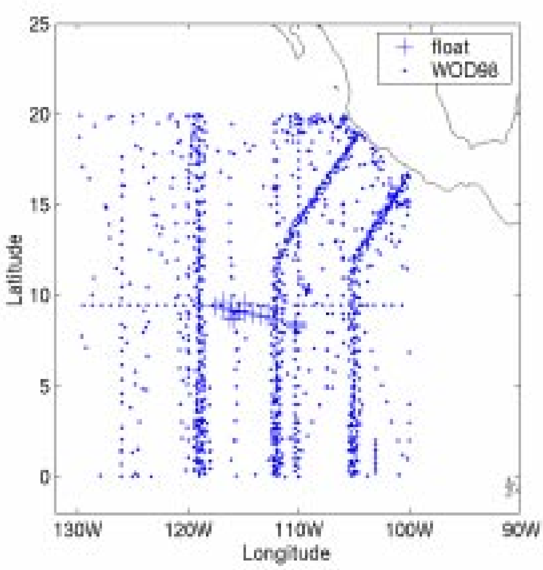

Fig. 1. Float profile locations (+) and selected nearby historical data from the WOD98 (·), from Pacific float CORC1118.

An example of this procedure is here illustrated by data from an eastern tropical Pacific float, CORC1118 (pers. comm. R. Davis). The float drifted westward from about 110°W to about 115°W, between 8°N and 10°N, during 1998 – 1999, in a region with a fair amount of historical data from the WOD98 (Fig. 1).

As the float moved westward, its salinity measurements drifted towards higher values relative to the estimated climatological salinity field (Fig. 2). In this region, the water has a tight θ-S relationship. For example, at 10°C, objective estimates of background salinity along the float trajectory fall within the range of 34.69 – 34.70, with the mapping errors in the range of 0.002 – 0.008. The float salinity measurements, however, drifted from 34.70 (profile #1) to 34.77 (profile #20). The wide range of salinity measurements obtained by the float along its trajectory is therefore obviously not due to the different water masses sampled, but is the result of sensor drift. In the case of this float, sensor drift towards salty values are expected as an anti-fouling coating on the conductivity cell ablates with time. This ablation changes the cell geometry, leading to salinity values that are higher later in the float's life.

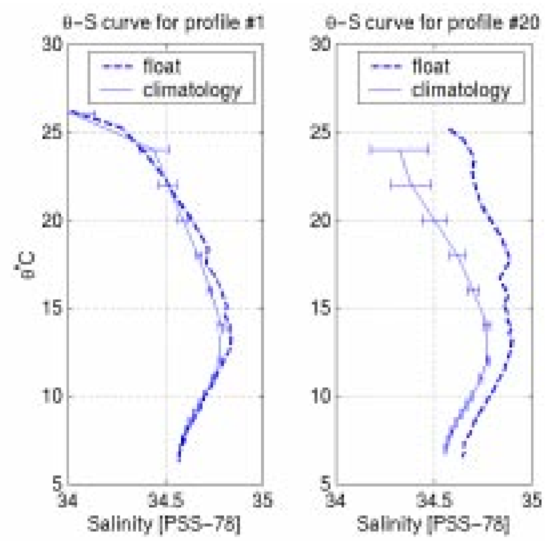

Fig. 2. θ-S relationships from uncalibrated float data (– –) and objective estimates (—), at the 1st and 20th profile locations of CORC1118. The error bars denote errors from the objective estimates. Note that the float salinity measurements drifted towards higher values from the 1st profile to the 20th profile.

Note that the salinity mapping errors naturally increase from 0.002 – 0.008 at 10°C (~ 330 m), to 0.027 – 0.075 at 20°C (~ 50 m), due to the greater variability at the shallower layers. While variability in the tropics is quite low at these levels, it can be higher elsewhere. Generally deeper profiles sample more stable θ-S relationships, which is one reason for a 2000 m target profiling depth for the ARGO floats.

It can be seen from Fig. 3 that the calibration procedure has made only slight adjustments to profile #1, but has made significant adjustments to profile #20, pulling the θ-S curve towards lower salinity values. Work is in progress to determine a realistic model that makes use of the errors from the objective maps to estimate the errors in the calibration.

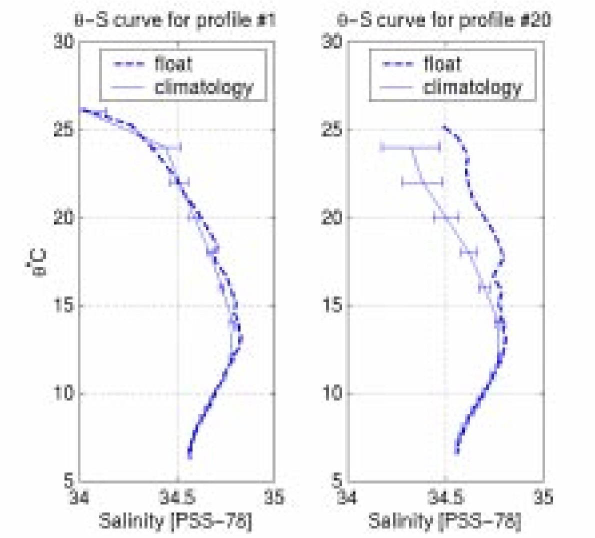

Fig. 3. Same as Fig. 2, except with calibrated float data (– –).

3. DISCUSSIONS

Due to the need to accumulate a time-series of float profiles to calculate the time-varying slope term, this is a delayed-mode calibration system. The calibration algorithm assumes that the conductivity measurements drift slowly over time, so it makes use of multiple profiles to estimate the correction term. Thus a stable calibration is expected to take a few months.

This calibration model works best for the parts of the ocean where the water has a near-constant θ-S relationship, such as the deep Pacific, where statistical methods give confident estimates of the climatological salinity field. In areas with great spatial and temporal variabilities, such as the subpolar North Atlantic (e.g. Dickson et al, 1996), statistical estimates are more uncertain, and so give rise to uncertain calibrations. Thus this model raises the issue that until accurate and stable conductivity measurements are achievable for these floats, frequent in-situ hydrographic observations at intervals less than the ventilation time-scale are needed for accurate profiling float salinity data calibration to be performed in areas with high variability.

Acknowledgements. We would like to thank Russ Davis for providing the CORC float data, and John Bullister for providing the CFC apparent ages. Don Denbo, Willa Zhu, Jason Fabritz and Kristy McTaggart are thanked for their assistance with data and programming. This project is supported by the National Ocean Partnership Program (NOPP).

4. REFERENCES

Dickson, R., J. Lazier, J. Meincke, P. Rhines and J. Swift, 1996: Long-term coordinated changes in the convective activity of the North Atlantic. *Progress in Oceanogr.*, **38**, 241 – 295.

Doney, S. and J. Bullister, 1992: A chlorofluorocarbon section in the eastern North Atlantic. *Deep-Sea Res.*, **39**, 1857 – 1883.

Emery, W. and J. Dewar, 1982: Mean temperature -salinity, salinity-depth and temperature-depth curves for the North Atlantic and the North Pacific. *Progress in Oceanogr.*, **11**, 219 – 305.

McIntosh, P., 1990: Oceanographic data interpolation: objective analysis and splines. *J. Geophys. Res.*, **95**(C8), 13 529 – 13 541.

Roemmich, D., 1983: Optimal estimation of hydrographic station data and derived fields, *J. Phys. Oceanogr.*, **13**, 1544 – 1549.

World Ocean Database, 1998: Ocean Climate Laboratory, National Oceanographic Data Center, Silver Spring, Maryland.